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1.1 Beam Position Monitoring with Cavity Higher Order Modes in the Superconducting Linac FLASH*

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1.1.1 Introduction

FLASH (Free Electron Laser in Hamburg§) is a user facility for a high intensity VUV-light source [1]. The radiation wavelength is tunable in the range from about 40 to 13 nm by changing the electron beam energy from 450 to 700 MeV. The accelerator is also a test facility for the European XFEL (X-ray Free Electron Laser) to be built in Hamburg [2] and the project study ILC (International Linear Collider) [3]. The superconducting TESLA technology is tested at this facility, together with other accelerator components.

1.1.1.1 *The TESLA cavity*

The TESLA cavities are used for acceleration in FLASH and the XFEL. The ILC will have similar accelerating structures. The TESLA cavities are superconducting 9-cell 1 m long structures (see Figure 1). A 1.3 GHz wave is input through a power coupler. Two HOM (Higher Order Modes) couplers extract energy from the resonant fields excited by the electron beams [4].

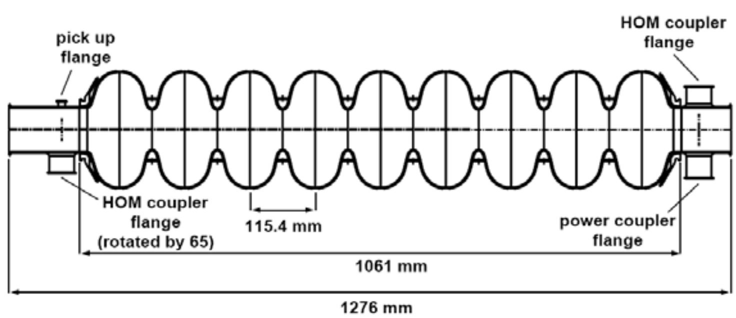

Figure 1: The TESLA cavity.

The HOMs are fields excited by the beam, which act back on the beam and can

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§The accelerator was known until recently as the VUV-FEL (VUV Free Electron Laser) and TTF2 (TESLA Test Facility – Phase 2)

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degrade its quality, e.g. the transverse emittance. Therefore it is important to damp them with the HOM couplers. Also, the amplitude of the excited transverse fields increases with the beam offset from the cavity axis, therefore centering the beam reduces them.

8 cavities are installed in a cryo-module and cooled at about 2 K. At the moment 5 cryo-modules have been installed at FLASH.

1.1.1.2 *Dipole modes as position monitors*

The HOM spectrum of a cavity contains passbands, each with 9 modes with similar field pattern [5]. Out of these, the dipole passbands are of highest concern since they are the main cause of multi-bunch transverse emittance growth. These are fields with two nodes on the azimuthal direction. Their amplitude is proportional to the offset of the exciting beam from the cavity axis. The linear dependence of the dipole modes on the beam offset makes them suitable to be used as BPMs (beam position monitors), similarly to cavity BPMs. Cavity monitors have a potential for very low resolution in comparison to other BPM types [6].

However, there are significant differences of the dipole modes in the TESLA cavities and the cavity BPMs. Each mode has two orthogonal directions, or two polarizations. In the BPM case these are horizontal and vertical, fixed by the pickup position. A pure horizontal or vertical beam offset will cause only one of these polarizations to be excited. For the accelerating cavities the field directions are rotated so that a pure horizontal offset will excite both polarizations. Another difference to the cavity BPMs consists in the split in the frequencies of the two polarizations. Moreover the polarization directions and frequencies are different from cavity to cavity. A more complicated calibration method is therefore necessary.

1.1.2 Preliminary Studies

Figure 2 shows the setup for studies on the use of the dipole modes as BPMs. The single-bunch beam is deflected to various transverse positions and angles in an accelerating module containing 8 cavities by two pairs of magnetic steerers. A dipole mode is chosen from the spectrum for a given cavity and measured with a spectrum analyzer. One conventional BPM at each side of the module is used to measure the beam position.

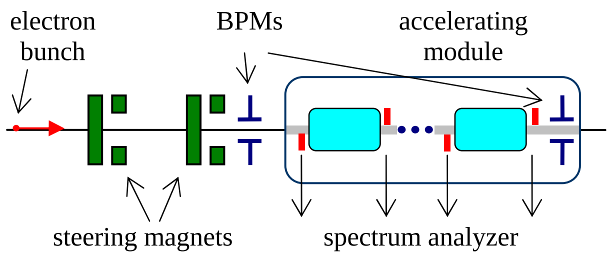

Figure 2: Measurement setup.

A mode in the first dipole passband of the first cavity of the first FLASH cryo-module is shown in Figure 3. One can distinguish the two polarizations with different frequencies. The first polarization has been found to respond to vertical beam movement, while the second is rather a “horizontal” mode.

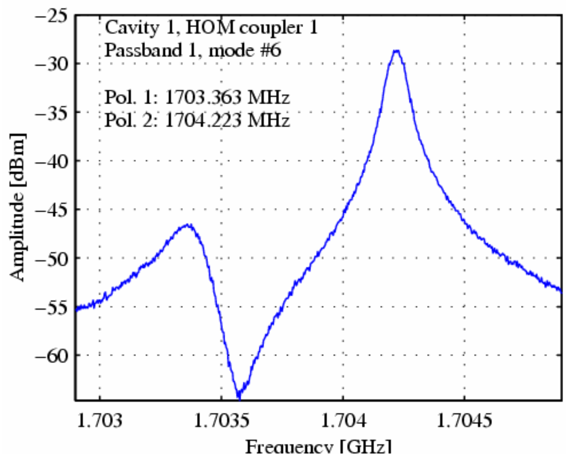

Figure 3: Dipole mode.

Horizontal and vertical position and angle scans have been made alternatively. The first polarization has been used for vertical scans, and the second for horizontal ones. Figure 4 shows a scan in each of the four transverse dimensions. The linear response of the modes amplitude to beam movement can clearly be seen. The deviation from linearity corresponds to beam jitter at the time of the measurement.

With alternative scans we could find the axis of the cavity, i.e. the beam trajectory for which a minimum in this dipole mode amplitude is obtained. Please note that the axis of other modes may be different, as already previously observed [7].

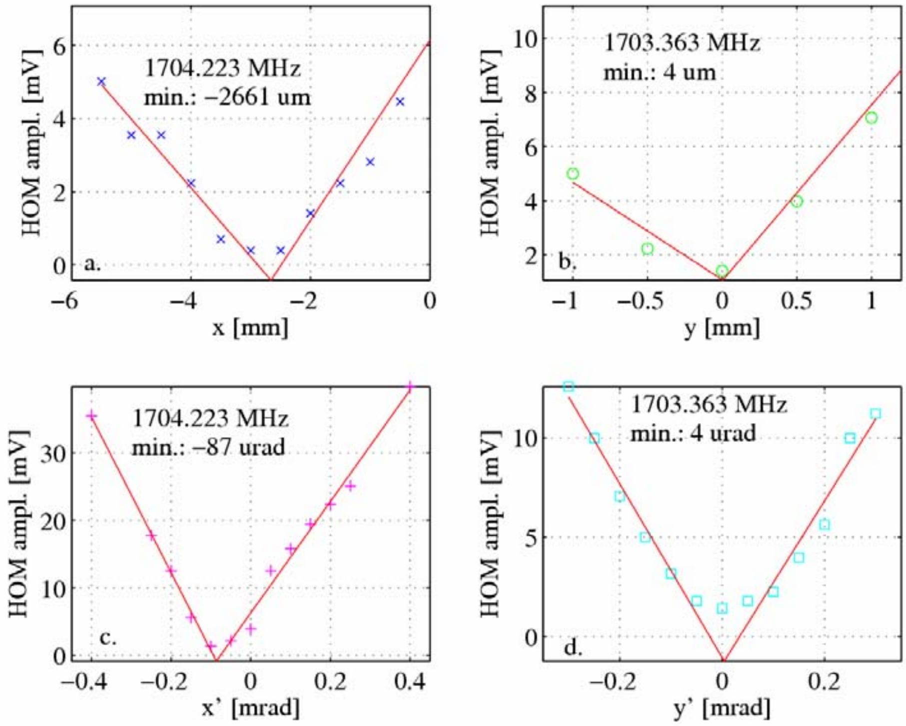

Figure 4: Scan of beam position in the 4D space.

1.1.3 The HOM-BPMs

1.1.3.1 *The HOM electronics*

Electronics has been designed and built for processing of one dipole mode from the HOM spectrum, similar to BPM-electronics. The principle of the electronics is shown in Figure 5 [8]. A bandpass filter selects from the spectrum a dipole mode at about 1.7 GHz. The signal is down-converted to about 20 MHz by mixing with a 1.68 GHz reference signal. The signal is then digitized.

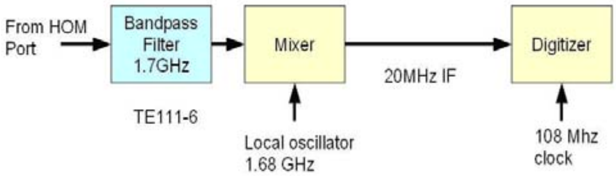

Figure 5: Principle of the HOM electronics.

Electronics modules have been installed at both couplers of all 40 cavities at FLASH. An example of a typical output signal from this electronics is shown in Figure 6. One can see the beating of the frequencies of the two polarizations of the dipole mode. For the first part of the signal the digitizers are saturated, due to a large beam offset.

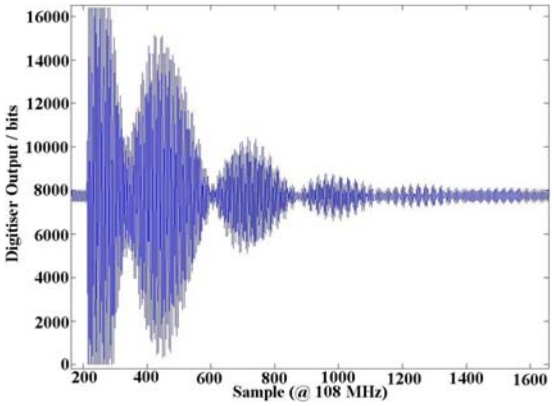

Figure 6: Output example of the HOM-BPM electronics.

This electronics should allow for the fast, simultaneous data collection from all HOM couplers. Moreover, it also provides information about the signal-phase, which allows us to distinguish between negative and positive beam offsets, and also to get information about the beam angle.

1.1.3.2 *Calibration*

In order to calibrate the HOM signals into beam position, the beam has been steered to various offsets and angles with a similar setup as the one in Figure 2. The HOMs have been recorded for each scan step, together with the setting of the steerers and the reading of the BPMs. Care has been taken to make scans large enough to include the axis of the mode.

As mentioned earlier, the calibration of the HOM-BPMs is somewhat more complicated than in the case of cavity BPMs. A method based on Singular Value

Decomposition (SVD) is used. This method allow for analysis of large data sets, without the need of a model for the accelerator. An orthonormal basis for the data from one 4D scan is found with the SVD. The amplitudes of the strongest basis modes are used. The cavity modes are then combinations of these basis modes. Linear regression correlates then the modes to the beam position at the cavity location as predicted by the conventional BPMs [8,9,10].

First estimations of the resolution achieved with the new calibration in a few cavities showed values of 5-10 μm rms [11]. Figure 7 shows a histogram of the residual between the position reading at one cavity and the prediction of the beam position at that cavity from the position measured in the two adjacent cavities. A resolution of 5 μm is obtained in this case. Theoretically, a much better resolution is achievable. A resolution of 1.5 μm has been previously observed [10]. Work is going on in order to improve the electronics and improve the calibration.

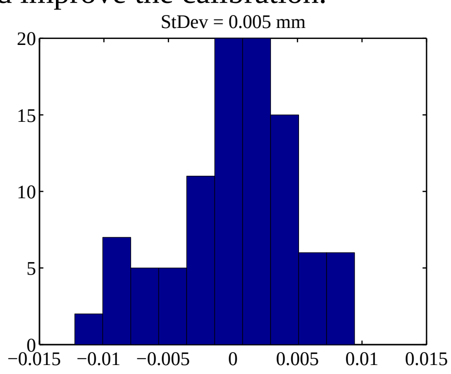

Figure 7: Histogram of the residual (in mm) of the beam position measured in one cavity against the prediction from two adjacent cavities.

1.1.3.3 *Integration of the HOM-BPM signals in the control system*

The calibration matrices have been used in the past for off-line beam position measurement tests. Currently work is being made to integrate the beam position measurement into the control system of FLASH: the Distributed Object Oriented Control System (DOOCS) [12]. A new server has been written for this purpose. The consistency of this server will be checked in 2007.

1.1.4 Summary and Outlook

The proof-of-principle for the use of HOMs as BPMs has been made. Electronics has been installed for monitoring one dipole mode in each of the 40 cavities at FLASH. Their calibration and the integration in the accelerator control system are under going. A resolution of 5-10 μm rms has been observed and 1 μm is thought possible through improvement of the electronics. After commissioning of the single-bunch calibration, multi-bunch signals will be studied.

Apart for measuring the beam position, the HOM-BPMs have been used to measure the relative position of the 8 cavities inside the cryo-module [9,10]. Also, by minimizing the raw dipole signals one can reduce the HOMs and therefore their effect on the beam.

The installation of such HOM-BPMs at cavities in the ILC may relax the requirements of the conventional BPMs in the main linac or even reduce their number and cost. Also it can help to control better the emittance growth.

1.1.5 References

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